NASA TT F-9188

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FACILITY FORM 602
N71-71179 (ACCESSION NUMBER)
27 (PAGES)
(NASA CR OR TMX OR AD NUMBER)
(THRU)
None (CODE)
(CATEGORY)

Translation of "Zur Messung der turbulenten Wandreibung mit dem Prestonrohr."
Year Book 1962, Wissenschaftliche Gesellschaft für Luft-und Raumfahrt, pp. 151-159.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON NOVEMBER 1964

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MEASUREMENT OF TURBULENT SKIN FRICTION WITH THE PRESTON TUBE[1]

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ABSTRACT

Turbulent boundary layers show a simple universal behavior adjacent to the wall. This is true for subsonic flows as well as for supersonic flows. It is shown how this fact may be used for the development of simple pressure probes to measure turbulent skin friction.

Dalhov

1. Introduction /151*

This article concerns a problem in aerodynamic measurement technique. It is known that a great part of the resistance to which a body is exposed in flow is determined by the sum of the aerodynamic frictional forces exerted upon its surface. The experimental investigation of the distribution of these frictional forces over the surface has hardly been possible heretofore, because the available methods of measuring local skin friction were too complex. A simple method, capable of filling this gap, was proposed in 1954 by J. H. Preston (ref. 1) for measurement of turbulent skin friction, but it was at first regarded with skepticism or, at least, considered valid only within limits. Later investigations, (refs. 2 and 3) demonstrated that this doubt was unwarranted.

The underlying principle of the new method of measurement is the universal structure of turbulent friction layers proximate to the skin. This fact, much

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[1]From the Hermann-Föttinger Institute for Flow Technique of the Technical University Berlin (Director: Prof. R. Wille).

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discussed, can be applied in an extraordinarily versatile manner for the construction of a workable skin shear stress probe.

2. Symbols

y	coordinate perpendicular to the skin
u	velocity parallel to the skin
v	velocity perpendicular to the skin
ϱ	density
μ	viscosity
ν	kinematic viscosity
T	temperature
a	velocity of sound
M	Mach number
τ	shear stress
u_τ	shear stress velocity
p	static pressure
P	Pitot pressure
l	Prandtl mixing
K	Karman constant ($K = 0.4$)
Pr	Prandtl number ($Pr = 0.72$)
r	recuperation factor ($r = 0.90$)
x	isentropic index ($x = 1.4$)
ω	exponent of the viscosity index ($\omega = 0.75$)

The index w represents the condition at the skin; overscoring ($\bar{}$) indicates the median value, and a prime ($'$) indicates the fluctuation value.

3. Mathematical Model for a Turbulent Friction Layer Proximate to a Skin

The state of motion of a turbulent friction layer in the vicinity of a skin is determinable by two hypotheses developed for this region, for a hypersonic as well as for a supersonic boundary layer. The first hypothesis offers a statement concerning the structure of turbulent fluctuating motion and is the known Prandtl equation of mixing

$$-\overline{u'v'} = l^2\left(\frac{d\bar{u}}{dy}\right)^2 \text{ with } l = Ky. \tag{1}$$

The second hypothesis offers a statement concerning the mean motion. We assume that in the layer proximate to the skin, the state of motion of the flow develops primarily through the entrainment of the flow remote from the skin. The effect of pressure and inertial stresses on the flow particles in this region is assumed to be of the second order. The flow layer proximate to the skin is thus treated in our model as a Couette flow or as a laminar flow (fig. 1). The equation of motion is then simplified to

$$\tau = \text{ const } = \tau_w. \tag{2}$$

Here, with consideration of variations of density in a compressible turbulent boundary layer, we first introduce for shear stress

$$\tau = \mu\frac{d\bar{u}}{dy} + \bar{\varrho}(-\overline{u'v'}) + \bar{u}(-\overline{\varrho'v'}) \tag{3}$$

Calculation for a laminar flow $\varrho'v' = 0$ is made from the continuity equation (ref. 4). The values of fluctuation obtained in the member $\mu du/dy$ are disregarded, because this laminar portion of the shear stress is known to be significant only in the area proximate to the skin, i.e., in the laminar underlayer. The shear stress equation is thus simplified to

$$\tau = \bar{\mu}\frac{d\bar{u}}{dy} + \bar{\varrho}(-\overline{u'v'}). \tag{4}$$

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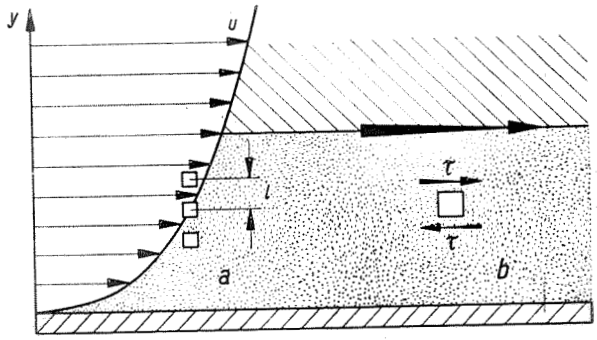

Figure 1. Model of a turbulent friction layer proximate to the skin; a = turbulent exchange of impulses according to the Prandtl mixing hypothesis; b = interpretation of the friction layer proximate to the skin as a Couette flow entrained from the outside.

Equations (1), (2) and (4) then yield a differential equation for the unknown velocity distribution[1]

$$\bar{\mu}\frac{d\bar{u}}{dy} + \bar{\varrho}K^2y^2\left(\frac{d\bar{u}}{dy}\right)^2 - \tau_w = 0. \tag{5}$$

4. The Skin Formula

For incompressible flow with μ = constant and ϱ = constant, integration of equation (5) is feasible. It yields the solution

$$\left\{\begin{array}{l} \varphi = 3{,}13\,\dfrac{1-\sqrt{1+0{,}64\,\eta^2}}{\eta} + \\ \qquad + 5{,}75\,\lg\,(0{,}8\,\eta + \sqrt{1+0{,}64\,\eta^2}) + 6{,}43 \end{array}\right. \tag{6}$$

with

$$\varphi = \frac{u}{u_\tau}, \quad \eta = \frac{u_\tau y}{\nu}.$$

The resulting integration constant has been so selected that from (6) for magnitude η there results the asymptotic solution (11b) with B = 5.1.

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[1]For further calculations for temporal median values, the transverse line is omitted.

If the general case of a compressible flow is under consideration, the closed solution of differential equation (5) is no longer possible. A good approximation in the form of two asymptotic solutions results, as can be subsequently determined for incompressible flow in comparison with the exact solution (6), if the friction layer near the skin is divided into a very thin layer proximate to the skin with preponderantly laminar friction and a thicker layer remote from the skin with preponderantly turbulent friction.

a) Laminar layer:

$$\mu \frac{du}{dy} - \tau_w = 0. \tag{7a}$$

The dependence of viscosity on temperature may be expressed by an exponential function.

$$\mu = \mu_w \left(\frac{T}{T_w}\right)^{\omega}. \tag{8a}$$

The equation of energy affords, as is known, a simple correlation between temperature distribution and velocity distribution in the boundary layer. For the case in which there is no heat exchange between the flow and the skin, equation

$$\frac{T}{T_w} = 1 - m_l^2 \tag{9a}$$

is valid, with

$$\left\{ \begin{aligned} m_l^2 &= \frac{\varkappa - 1}{2} \sqrt{Pr} \left(\frac{u}{a_w}\right)^2 = \\ &= \frac{\frac{\varkappa - 1}{2} \sqrt{Pr}\, M^2}{1 + \frac{\varkappa - 1}{2} \sqrt{Pr}\, M^2}. \end{aligned} \right. \tag{10a}$$

The differential equation (7a) then has the solution

$$\frac{u}{u_\tau}\,\varphi_l = \frac{u_\tau\, y}{\nu_w} \tag{11a}$$

with

$$\varphi_l = \frac{1}{m_l}\int (1 - m_l^2)^\omega\, dm_l. \tag{12a}$$

b) Turbulent layer:

$$\varrho\, K^2 y^2 \left(\frac{du}{dy}\right)^2 - \tau_w = 0. \tag{7b}$$

The dependence of density on temperature is given by the equation of state, where the static pressure as usual is assumed to be constant over the boundary layer thickness

$$\varrho = \varrho_w \left(\frac{T}{T_w}\right)^{-1}. \tag{8b}$$

The energy equation, analogous to (9a) yields

$$\frac{T}{T_w} = 1 - m_l^2 \tag{9b}$$

with

$$m_i^2 = \frac{\varkappa - 1}{2}\, r \left(\frac{u}{a_w}\right)^2 = \frac{\frac{\varkappa - 1}{2}\, r M^2}{1 + \frac{\varkappa - 1}{2}\, r M^2}. \tag{10b}$$

Differential equation (7b) then has the solution

$$\frac{u}{u_\tau}\varphi_t = A \lg \frac{u_\tau y}{\nu_w} + B, \tag{11b}$$

with

$$\varphi_t = \frac{1}{\sqrt{n_t}} \arcsin m_t. \tag{12b}$$

Functions φ_1 and φ_t are shown in figure 2. For low Mach numbers both functions tend towards unity. Equations (11a) and (11b) are converted into the known asymptotic skin formula for the incompressible turbulent boundary layer. It follows then that constants A and B in equation (11b) are identical with the measured values A = 5.75 and B = 5.1 in the incompressible logarithmic boundary layer.

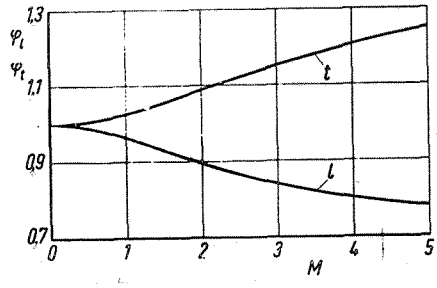

Figure 2. Functions φ_1 and φ_t dependent on the Mach number.

In the area near the skin, therefore, turbulent hypersonic and supersonic boundary layers not additionally cooled or heated from the skin are described by the same equations (11a) and (11b). This fact signifies an inclusive principle of order for the representation of experimental results, as will be impressively demonstrated in figure 3. The measurements plotted here span an area that extends from incompressible water flow in a pipe (J. Nikuradse) to a

hypersonic flow with Mach number $M_\infty = 5.8$ (R. H. Korkegi). The graph contains only measured values of the zone near the skin, for which here the first fifth of the boundary layer density δ was selected.

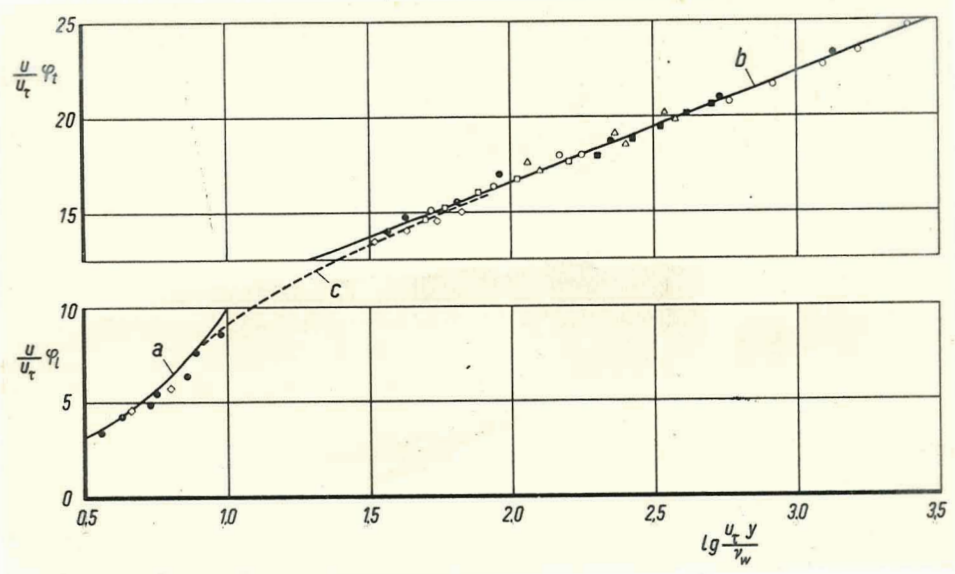

Figure 3. Distribution of velocity of turbulent friction layers proximate to the skin for hypersonic and supersonic flows without heat exchange.

○	→ 0	*J. Nikuradse*	[7]
●	→ 0	*J. Laufer*	[8]
□	1.73	*E. W. Fenter, C. J. Stalmach*	[9]
■	3.68		
△	2.0	*J. F. Naleid, M. J. Thompson*	[10]
◇	4.93	*R. K. Lobb, E. M. Winkler, J. Persh*	[11]
◆	5.8	*R. H. Korkegi*	[12]

Curve a according to equation (11a), curve b according to equation (11b), curve c according to equation (6).

5. Theoretical Example of an Apparatus for Measurement of Skin Friction

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Let us again summarize the results of the preceding chapter. The state of motion of a turbulent friction layer proximate to a skin is accessible by a

simple model of the theoretical treatment. Simple equations (11a) and (11b) result. These relationships have been thoroughly confirmed experimentally for both hypersonic and supersonic boundary layers. Because of the limited number of parameters that develop, a universal law is ascribed to turbulent friction layers proximate to the skin. We will now show by a theoretical example how to derive a rational method from this universal relationship for measurement of local turbulent skin shear stress.

We refer to the measuring instrument illustrated in figure 4, arranged in the friction layer proximate to the skin. A very small Pitot tube is fixed by two pins at a distance h from the skin, in which there is a static pressure aperture. The friction layer proximate to the skin yields the data P and p. An ideal ram point flow is established for the Pitot tube which is influenced neither by the proximity of the skin nor by the viscosity of the flowing medium. At the pressure aperture, the undisturbed static pressure prevailing at the point of the Pitot tube mouth is measured. Between u_h and M_h on one hand, and P and p on the other, quite simple gas dynamic relationships are now valid for this system. For $M_h < 1$ the equation of an adiabatic ram point flow is used, and for $M_h > 1$ the Rayleigh Pitot tube equation is substituted. These relationships are introduced into skin equations (11a) and (11b). The skin equations thus converted are shown in figure 4. A method of representation is selected which is particularly suited for direct determination of skin shear stress from the measured values P and p of our instrument. We see here also that two asymptotic solutions are involved. For incompressible flow $(P - p)/p \longrightarrow 0$ the exact course of the curve is shown as obtained from equation (6). For practical application of this diagram we must think of the remaining curves as rounded off in a similar manner.

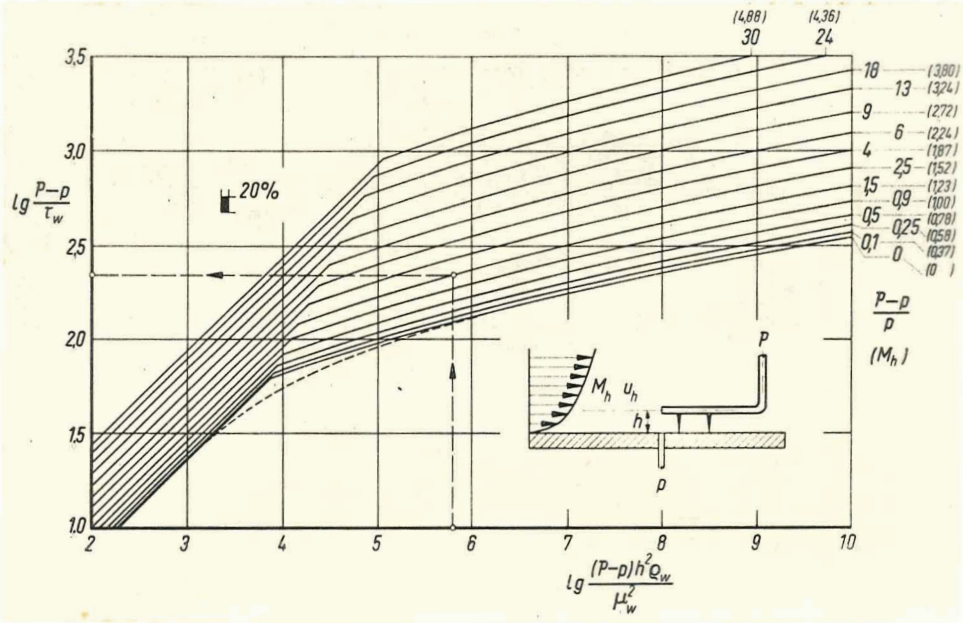

Figure 4. Pitot tube as measuring device for skin friction in turbulent hypersonic and supersonic boundary layers.

The skin shear stress is determined from this diagram as follows: we measure the pressure difference P - p, static pressure p, and the skin temperature T_w at the point of measurement. Density ϱ_w is calculated from the equation of state and viscosity μ_w from the Sutherland formula. Height h is a property of the measuring instrument and is built-in, so to speak, thus giving the abscissa $(P - p)h^2\varrho_w/\mu_w^2$ and the parameter $(P - p)/p$. The pressure difference P - p, divided by the read-off ordinate, yields skin shear stress τ_w.

6. Elaboration of the Measuring Principle

The result of the preceding chapter now undergoes an important generalization. The Pitot tube in combination with a static pressure aperture does not constitute the sole device, whereby skin shear stress can be determined from a pressure measurement within the flow zone of a turbulent friction layer near /154

the skin. Any small immersed barrier is usable within the range of validity of the skin formula. Instead of the pressure difference P - p, there is then the specific pressure difference Δ p measured at the barrier. This fact constitutes the basis for the development of a practical, workable skin shear stress probe, a problem which will be treated in sections 7 and 8.

The above enunciated principle will be proved by a dimension analysis (ref. 5). For this purpose we consider a test body of any given geometric form, with whose geometrical contour two pressure apertures are in fixed connection. The interrelationships become especially clear if the test body is placed successively first in an undisturbed parallel flow and then in a friction layer (fig. 5).

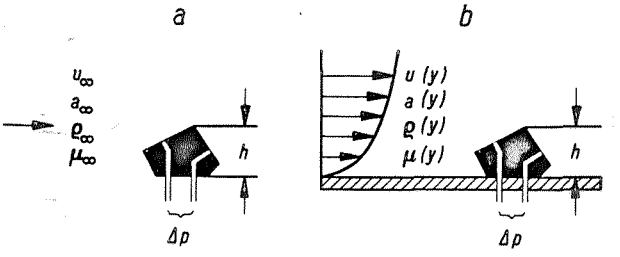

Figure 5. Elaboration of the measuring principle; a) test body in a uniform parallel flow; b) test body in a friction layer.

6.1 Test body in a parallel flow

The flow state about the test body is given by the velocity of flow from the initial direction u_∞ , the Mach number of the flow from the initial direction or the velocity of sound a_∞ , density ϱ_∞ , viscosity μ_∞ , as well as size h of the body. More precisely formulated: the differential equation involved in this problem would in its theoretical final integrated form contain exactly the above mentioned five magnitudes in addition to the value to be calculated, e.g., resistance, lift, pressure distribution.

We find especially that

$$\Delta p = f_1(u_\infty, a_\infty, \varrho_\infty, \mu_\infty, h). \tag{13}$$

is also valid.

6.2 Test body in a friction layer

In perfect analogy with the case of the test body in a parallel flow, we have first

$$\Delta p = f_2[u(y), a(y), \varrho(y), \mu(y), h]. \tag{14}$$

as valid.

It is now essential--and this is the basic fact derived from the skin formula--that the dependence of the individual values on skin distance y is completely determined by the state of flow at the skin. Thus functions u(y), a(y), ϱ(y) and μ(y) are unequivocally determined by the values of shear stress velocity u_τ, velocity of sound a_W, density ϱ_W, and viscosity μ_W. The reader can find this in equations (8) to (11). Hence, it follows that

$$\Delta p = f_3(u_\tau, a_w, \varrho_w, \mu_w, h). \tag{15}$$

According to the principle of dimension analysis (Buckingham's Theorem II), the six magnitudes present in these equations which collectively include the three basic units (kg), (m) and (sec) can be condensed to 6 - 3 = 3 dimensionless characteristic magnitudes. For our test body in parallel flow, we then obtain from (13) the known characteristic magnitude equation

$$\frac{\Delta p}{\varrho_\infty u_\infty^2} = F_1\left(\frac{u_\infty h}{\nu_\infty}, \frac{u_\infty}{a_\infty}\right). \tag{16}$$

Similarly we obtain from (15) for our test body in the turbulent friction layer the characteristic magnitude equation

$$\frac{\Delta p}{\varrho_w u_\tau^2} = F_2\left(\frac{u_\tau h}{\nu_w}, \frac{u_\tau}{a_w}\right). \tag{17}$$

According to a further principle of dimension analysis, it is possible to raise the individual characteristic magnitudes to any power and multiply them with one another, in order to obtain new forms of a characteristic magnitude equation. If in (17) both right-hand magnitudes are squared and then multiplied by the left-hand magnitude, we have with /155

$$u_\tau^2 = \tau_w/\varrho_w \quad \text{and} \quad a_w^2 = \varkappa p/\varrho_w$$

the significant form

$$\frac{\Delta p}{\tau_w} = F_3\left(\frac{\Delta p\, h^2 \varrho_w}{\mu_w^2}, \frac{\Delta p}{p}\right). \tag{18}$$

We have, therefore, obtained an equation that offers a statement completely analogous to that of figure 4, this time, however, for a barrier of any geometry.

7. A Workable Skin Stress Probe

The possibility now afforded by the generalized characteristic magnitude equation (18) is obvious. We are in a position not only to design a skin shear stress probe that offers advantageous operation in measurement technique, but we are also able to use a structural form that can be made with particular ease. It is only important that we keep the underlying principle of the measuring method constantly before our eyes. The local state of the boundary layer flow, adjacent to the skin, which contains the desired data concerning local skin

friction, must be sensed by an instrument. As sensing organ we introduce a barrier element of predetermined form in the friction layer proximate to the skin, and we record a pressure difference Δp evoked by the flow around the barrier. For specific areas of application it should be possible to produce the instrument in very small dimensions. This may be necessary when local skin friction changes substantially even over a short distance. The measuring value must then be taken from a narrowly limited flow region in order to regard it as representative of the local flow state. In another case a small instrument may be needed if the boundary layer to be investigated is thin. The measuring device must, of course, always be located within the range of validity of the universal skin formula. This range amounts to about 1/5 to 1/20 of the boundary layer density δ, where the lesser value is valid for boundary layers near the point of flow separation.

When, with these considerations, we have decided on a specific arrangement, the universal characteristic magnitude equation (18) must be solved for this geometry. This will only rarely be possible by theoretical means, as demonstrated by the system of the Pitot tube in conjunction with a static pressure aperture in section 5. Here, we must rely on experimentation. This by no means signifies that every instrument must be calibrated under conditions of extreme turbulence with known skin shear stress. Rather, it is the great advantage of the dimensionless characteristic magnitudes that we can reduce the use of experiment, as is generally the case in model technique. An example of this is given.

The characteristic magnitude equation (18) is to be solved for an experimentally determined probe form that appears to be advantageous, first only for the incompressible flow range $\Delta p/p \longrightarrow 0$. The experiment can be conducted in

such a way that for the whole calibration only a single experimental boundary layer with known skin friction is needed. We must then prepare a rather large number of probes with the utmost uniform gradation of dimensions; these we introduce successively in the region proximate to the skin in a turbulent calibrating boundary layer. Secondly, an experimental program is possible in which the whole calibration can be effected with a single probe. Here the skin friction of the turbulent calibrating boundary layer, into which the single probe is built, must be variable by change of flow velocity. Both methods of calibration have been tested in practice. The reader will find an example in figure 7 of the next section.

With regard to experimental apparatus let us note that for incompressible flow, turbulent flow in a tube is the ideal calibrating flow because here the skin shear stress, otherwise so difficult to measure, is obtained immediately from the pressure drop along the tube. For supersonic flows calibration could be effected in a two-dimensional Laval nozzle with one flexible wall that allows variation of the Mach number and one fixed wall that is a seat for the sounds to be calibrated and for a skin friction measuring device.

8. Structural Forms of Skin Shear Stress Probes

The guiding concepts set forth in the preceding section for construction of a skin shear stress probe permit possibilities of additional modification. In figure 6 three structural forms are illustrated.

Structural form I we know from section 5. For the system consisting of a /156
Pitot tube and a static pressure aperture the whole characteristic magnitude equation (18) was solved. The instrument is operational for measurement of skin friction in turbulent hypersonic and supersonic boundary layers. There is

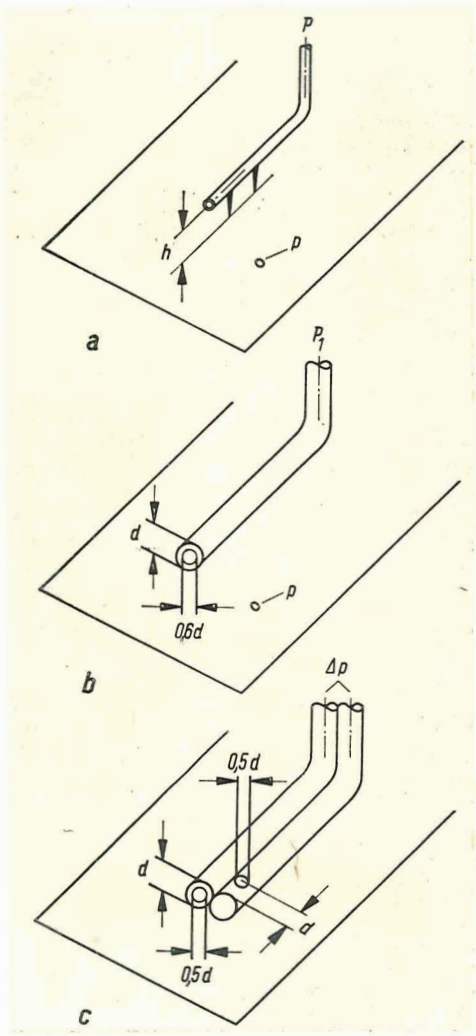

Figure 6. Structural forms for skin shear stress probes; a) structural form I: Pitot tube; b) structural form II: Preston tube; c) structural form III: two-aperture probe.

a decisive disadvantage, however, which opposes this advantage. If a very restricted height is required for the instrument in thin boundary layers, the necessary reduction in size of the Pitot tube is hardly feasible. Instead of the circular form of the Pitot tube, a flattened tube could obviously also be used.

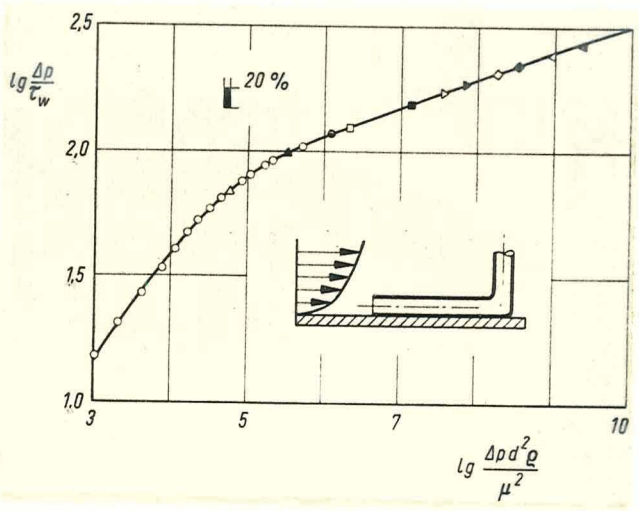

Figure 7. Calibration of Preston tubes in a turbulent tube flow.

	d [mm]	U [m/sec]
○	0.73	3 – 40
△	0.30	40
▲	0.60	
○	0.73	
●	1.07	
□	1.36	
■	3.06	
▷	4.74	
▶	6.33	
◇	9.52	
◆	12.7	
◁	20.1	
◀	30.7	

U ≈ velocity in tube center.

Structural form II was proposed as a skin shear stress probe by J. H. Preston in 1954 (ref. 1). This small tube applied against the skin has been known since then as the Preston tube. The measuring value is again a ram pressure; now, however, because of the velocity distribution ahead of the tube, it is additive over the entire aperture surface (the manner can not be immediately determined). Figure 7 shows the experimentally determined characteristic

magnitude relations for Preston tubes in the incompressible flow zone. A turbulent tube flow serves as calibration flow. The two series of measurements selected from many experiments again show impressively the equivalence of the the two calibration methods described in the preceding section. To facilitate use, table 1 shows the numerically exact calibration curve for Preston tubes.

Table 1. Universal calibration curve for Preston tube

$\lg \frac{\Delta p\, d^2 \varrho}{\mu^2}$	$\lg \frac{\Delta p}{\tau_w}$
2.0	0.652
2.5	0.902
3.0	1.150
3.5	1.385
4.0	1.588
4.5	1.766
5.0	1.898
5.5	1.993
6.0	2.063
6.5	2.120
7.0	2.176
7.5	2.232
8.0	2.290
8.5	2.347
9.0	2.402
9.5	2.453

The Preston tube constitutes certainly the simplest conceivable form of a skin shear stress probe. Production, of even the smallest size, presents hardly any difficulty. Using a 0.3 mm capillary spring, such as is used for drawing purposes, we can quickly make an extremely small Preston tube for use in very thin boundary layers.

In a comprehensive measuring program, the use of both probe forms I and II is quite expensive, because each point of measurement must be provided with a static pressure aperture. In three-dimensional boundary layers, for which after testing (ref. 6) the universal skin formula is retained unaltered, the use of these two probes in the illustrated arrangement is no longer possible.

Because pressure distribution is also three-dimensional, the static pressure (which, of course, would represent the undisturbed pressure at the probe site) can no longer be taken laterally from the probe.

Structural form III needs no static pressure aperture on the surface. This instrument consists of two small parallel tubes of equal diameter d. Both tubes are applied against the skin. One tube remains open at the front, like the Preston tube, and the other is closed at the front and has an aperture on the upper side at a distance d from the front edge. The pressure difference Δp is taken between these two openings. This proposal means, therefore, that the universal characteristic magnitude equation (18) can be used. Such a probe would be most advantageous for extensive shear stress measurements in incompressible flows, because here the static pressure is not required at the measurement point for determination of skin shear stress. The probe can be placed from outside at any point on the surface. Once the characteristic magnitude equation has been determined by calibration, the measured value Δp immediately yields the skin shear stress at this point.

9. Experiments

The experimental testing of the skin shear stress probes remains to be done. First we must develop a control that determines whether or not our probes in this or that turbulent boundary layer yield the correct skin shear stress. The measuring device in figure 8 was designed for this purpose. The skin shear stress probe to be tested is a Preston tube, and the control instrument a surface grid. This device consists of an extremely flat blade extending outward perpendicular to the skin and level with the flow, over which a pressure difference Δp is measured. Because the barrier is enough to be within the

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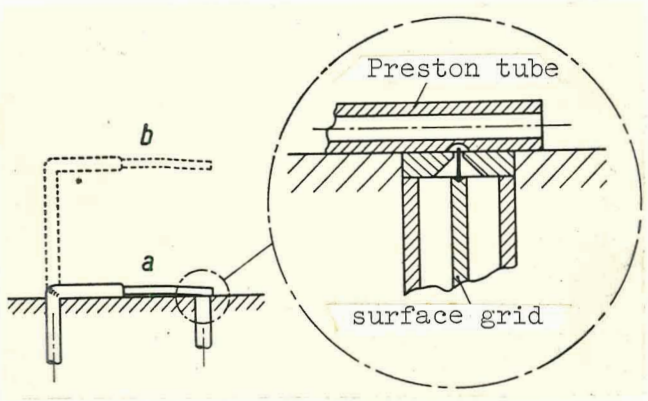

Figure 8. Combined device consisting of Preston tube and surface grid; a) Preston tube reading; b) surface grid reading.

linear profile of velocity of Newton's law of viscosity for the laminar underlayer, the measured pressure difference is unequivocally correlated to the skin shear stress. This fact is sufficient for most precise testing by a corrently planned series of tests of the Preston tube as skin friction measuring device for the incompressible flow zone.

First experiment: The measuring arrangement in figure 8 is placed in a fully developed turbulent tube flow. The indications of the Preston tube and of the surface grid for different flow velocities are calibrated against the skin shear stress following the pressure drop along the tube.

Second experiment: The tube length used is shortened so that the unchanged measuring device, left in place, is now located in the thin boundary layer of a turbulent tube inlet flow. The two shear stress values for different flow velocities, which can now be determined by the previous calibration from the indication of the Preston tube and the surface grid, are compared.

This experiment is described in more detail in references 2 and 3. The Preston tube yields precisely the same shear stress values as the surface grid

for the tube inlet flow. Since the boundary layer thickness of the inlet flow is small in comparison to the radius of the tube, this boundary layer may be compared with the boundary layer of a flat plate. This would, however, unequivocally refute the view, variously expressed in recent years, that the completely developed turbulent tube flow and a turbulent boundary layer of a plate obey two somewhat different laws relating to skin, and that Preston tubes calibrated in a tube flow therefore cannot be used for determination of shear stress in a plate boundary layer. This justifies us to continue with the experimental series.

Third experiment: A measuring device, figure 8, is now located in the /158
turbulent boundary layer of a flat plate in a parallel flow. The indication of the surface grid is calibrated against the skin shear stress indicated by the Preston tube for different flow velocities.

Fourth experiment: A shoulder is established on the plate to impart a rise in pressure to the boundary layer by damming up the flow (fig. 9). The distribution of the skin shear stress ahead of this shoulder is measured, first with the surface grid calibrated in the third experiment and subsequently with the Preston tube, without continuous rebuilding of the apparatus[1] (as would properly be correct), but by displacement of the shoulder toward the point of measurement. The two methods are not entirely identical, because with displacement of the shoulder the condition of flow from the initial point changes because of the increasing thickness of the boundary layer in the direction of flow. The difference is insignificant, however, because the only interest is the comparison of shear stress values yielded by the surface grid and the Preston tube.

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[1]In rebuilding the extremely sensitive surface grid a change of the previously determined calibration is hardly avoidable.

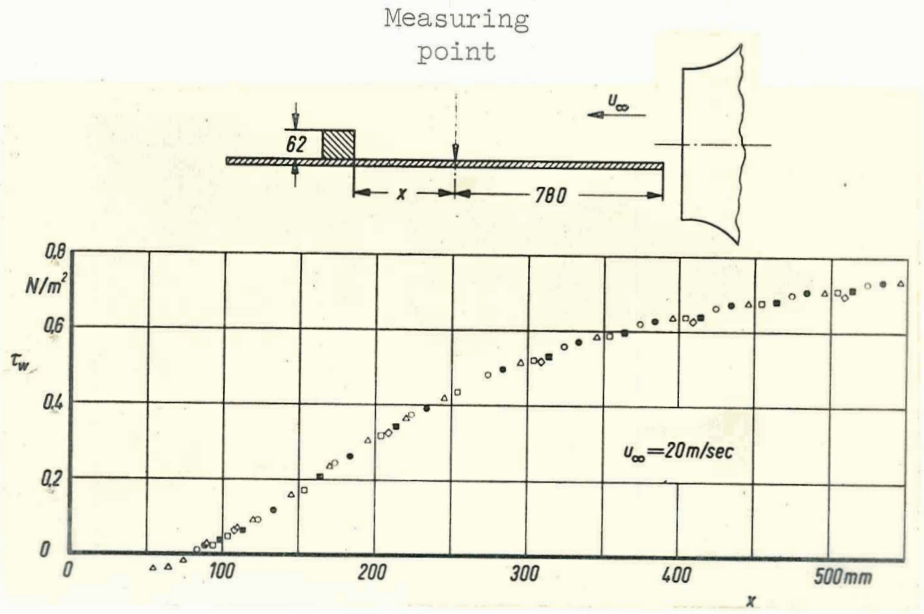

Figure 9. Skin shear stress measurements in a constricted turbulent boundary layer ahead of a shoulder.

△	surface grid	$h \approx 0.1$ mm
○	Preston tube	d = 0,8 mm
●		1,2
□		2,0
■		3,0
◇	2-aperture probe	d = 2.0 mm

The result of this experiment is shown in figure 9. The course of shear stress determined with four Preston tubes with application of the universal calibration curve of figure 7 is thus in complete agreement with the control values determined by the surface grid. This is equally true of the values of a two-aperture probe of structural form III, here used for the first time. The fact should be noted that both skin shear stress probes operate reliably also at the point of flow separation, in the region of very slight skin shear stress. On the basis of theoretical results it had long been assumed that this method of measurement would fail at this point.

10. Concluding Remarks

We have become acquainted, in a barrier with two points for taking of pressure readings, with a system which, when placed in a turbulent boundary layer proximate to the skin, permitted determination of local skin shear stress. For an incompressible flow, only the additional measurement of the pressure difference between the two pressure reading points was required. It is perhaps fitting to mention here a completely analogous measurement method in applied flow technology. This refers to methods of through-put measurements in pipes, which have as their point of departure a disturbance of the pipe geometry. There are always two points of pressure reading in the zone of disturbance, at which a pressure difference is measured and correlated to the amount of through-put. Here also, as in the case of our skin shear stress probes, a great number of configurations is conceivable and in use. The best known are nozzles, diaphragms and Venturi tubes which operate with a narrowing of the pipe cross section. A displacement body in the flow or an exactly determined sharp bend in the pipe are, however, also used for through-put measurement. Finally, any geometry is also operable after calibration for the through-put measurement.

Discussion

A. Naumann (Aachen): The work of I. Rechenberg could well be considered a continuation of the work of T. E.Stanton, who attempted as early as 1920 to measure local surface friction with small flat Pitot tubes, later known as Stanton tubes.

I. Rechenberg: In certain respects the Preston tube can be considered an elaboration of the Stanton tube. The Stanton tube, which is a flat Pitot tube with the lower wall formed mostly by the surface subject to flow, dams only the laminar lower layer. It must, therefore, be extremely low, in certain cases

only a few hundredths of a millimeter in height. The Preston tube was then developed, as it became clear that in a turbulent boundary layer not only the linear distribution of velocity given by the Newton law of viscosity in the im- /159
mediate vicinity of the skin, but also the associated turbulent flow layer in a zone (which in many cases comprises a 10 to 100-fold thickness of the laminar underlayer) are unmistakably correlated to the local skin shear stress. The simpler Preston tube was therefore developed from the extremely sensitive Stanton tube.

H. Ludwieg (Göttingen): How could you carry out a reliable calibration measurement with the Preston probe if the shear stress distribution in the direction of the periphery of the tube fluctuated so?

I. Rechenberg: The calibration of the Preston tube (fig. 7) took place in the completely turbulent tube flow after a flow through-put course equal in length to 80 tube diameters. By measurements at the head of this tube in the thin inlet boundary layer, significant variations of skin shear stress were later determined in the peripheral direction of the tube (refs. 2, 3). An immediate check of the distribution of the skin shear stress at the calibration point showed, however, no further irregularities in the periphery of the tube. The original wave formed pattern was completely smoothed after the through-put of 80 tube diameters.

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